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ESTABLISHING RELIABILITY GOALS FOR
NAVAL MAJOR CALIBER AMMUNITION

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In this study, we describe a decision process for establishing the threshold reliabilities for components of naval major caliber ammunition. A measure of reliability performance is described which relates directly to the weapons system's performance in a naval gunfire support environment. We use a simulation model to establish this relationship, a regression metamodel to estimate its parameters, and a simple decision process to specify component reliability thresholds which ensure that the ammunition is mission effective. We present this paper as an example of the integration of discrete event dynamic system analysis within a decision process.

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1. INTRODUCTION

The United States Navy purchases millions of dollars worth of major caliber ammunition each year to supply its warships. These ships have missions ranging from air defense to gunfire support of amphibious forces on land. The rounds of ammunition purchased are each individual systems subject to various forms of failure, and are purchased by component. There currently exists no systematic method for determining the minimum acceptable reliability level for round components, reliability levels are currently established rather arbitrarily, but with some total system reliability in mind.

The reliability of each of the components impacts the effectiveness of the weapon system and subsequently the effectiveness of the battle force. In order to procure and maintain ammunition which will provide adequate utility to Naval forces, there must be a clear understanding of this relationship of ammunition reliability and force effectiveness in various missions.

Consider a single round of major caliber ammunition which is comprised of a small number of components, including fuses, primers, propellant igniters, propellant, propellant casing, case plug, projectile and explosive. Each of these major components is in turn an assembly of a number of subcomponents. A round may experience failures in each of these subcomponents. While some of the possible failures result in preventing an effective round from arriving at the target, other failures prevent the gun or gun cluster from being fired for some period after the failure. In relating reliability performance to battle force performances, attention must be paid to

time sensitive situations such as self-defense. The proper measure of effectiveness, and implied optimal reliability, must take into account the cost of extra reliability, the value of the target, and the impact of modes of failure on performance.

The objective of this research is to establish reliability performance measures, and to specify minimum reliability goals for major caliber ammunition used in Naval Gunfire Support (NGFS) system. The reliability of ammunition and gun system must be expressed in terms of battle goals which include mission time, average casualty rate over mission lifetime, and the percentage of opponent's destructive power disabled at arbitrary time D. Then the decision maker has the ability to measure reliability performance in terms of the battle goals with which he is used to dealing.

The approach we took in this research is described in Figure 1.1. We first developed a simple measure called *ef* which is a function of reliability measures of individual components of the ammunition and gun system. The (theoretical) *ef* measure represents the expected number of effective rounds per unit time. The round is considered to be effective if it gets out of the barrel, hits the target and detonates successfully.

In order to determine reasonable reliability thresholds for ammunition, we must analyze the integrated system involving rounds, guns, targeting and scheduling. We compiled the data from various sources including Joint Munitions Effectiveness Manuals (JMEMS) and the OP-03 Material Readiness Data Base (MRDB) on the component reliability and gun reliability. This information is used to generate the NGFS scenario data file for simulation.

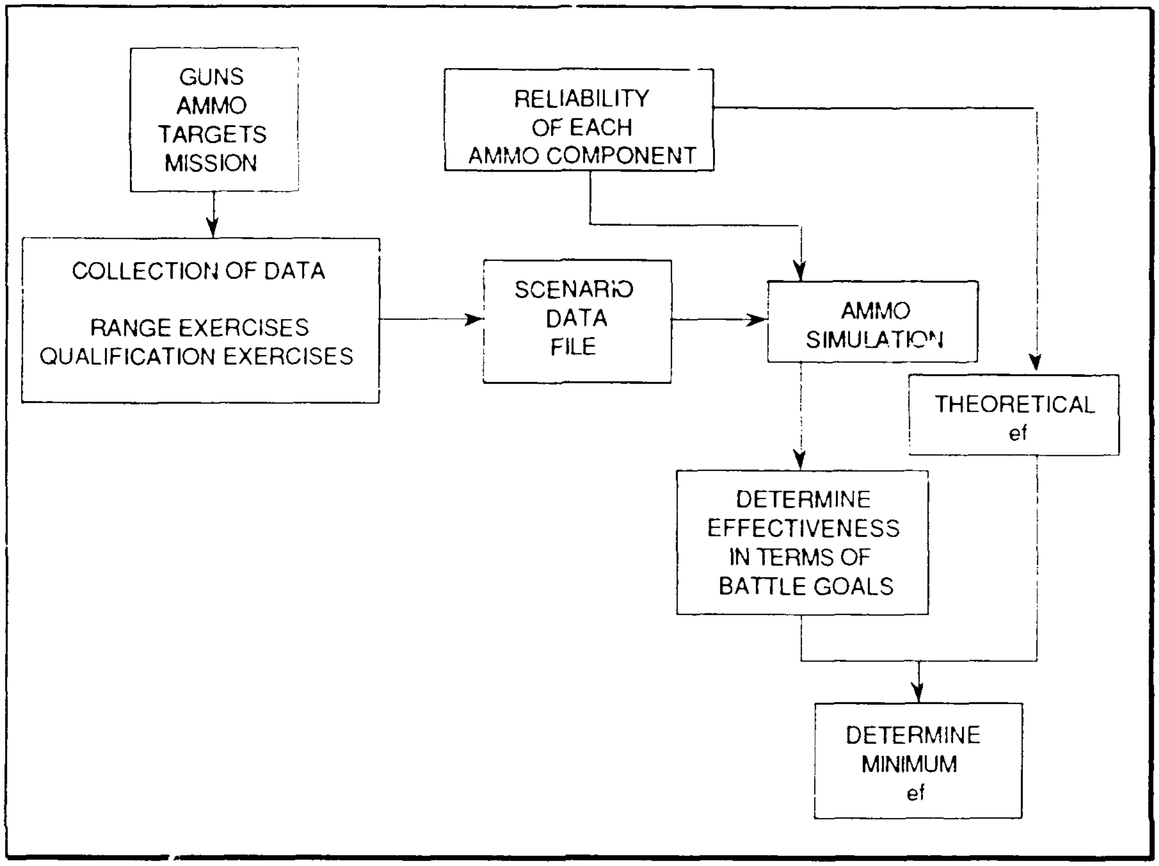

Figure 1.1. Flow Diagram of Reliability Goal Determination

We developed a simulation model to find the relationship between *ef* values and the battle goals which we call standard performance measures. The model is designed to simulate the NGFS scenarios to mimic the spotting, communication and targeting. The simulation results show that the *ef* values are highly correlated with the standard performance measures. They explain variability in observations of the standard performance measures for different component reliability configurations. Thus the decision maker is able to determine the effectiveness of ammunition in terms of battle goals. He can find the minimum (or critical) *ef* value which is still mission effective.

This will support his decision making process on procurement and surveillance. In procurement decisions, he can specify reliability values for components and subcomponents which meet minimum requirements for *ef* in a most economical way. Ammunition surveillance is the practice of removing several rounds from a stockpiled lot of ammunition and testing the reliability of the rounds or of the components. He then can decide whether or not to perform some sort of rework on an ammunition lot to improve the reliability to bring it to mission effective status. Currently the acceptance criteria for pronouncing a stockpiled lot fleet-ready are ad hoc. Our research proposes replacing the current surveillance test criteria with those that will ensure that the lot tested exceeds minimum *ef* in efficiency.

The results of our research can also be utilized to study the impact on marginal incremental improvements in component reliability for contractors or procurement agents. We provide an important set of tools useful in managing procurement and surveillance of ammunition.

The structure of this report is as follows. In Section 2, we develop a measure of performance of the gun-round system, *ef*, which represents the number of effective rounds per unit time. A simulation model is described in Section 3, which is used to estimate the effectiveness of NGFS given the *ef* values. In Section 4, we explain how to run the simulation program, and the statistical analysis of simulation results. We also describe in some detail the variance reduction techniques applied to our simulation study, which results in substantial improvement of simulation output. Section 5 includes the conclusions and future research.

2. MEASURING PERFORMANCE OF MAJOR CALIBER AMMUNITION

In this section we begin our exploration of the performance characteristics of the naval gunfire support system. In particular, we want to establish an appropriate performance measure to predict variations in the effectiveness of naval gunfire with respect to changes in round component reliabilities.

The execution of an amphibious assault by combined naval and marine forces can be conceptually divided into two distinct phases. Phase one, which we shall call **preemptive shelling**, occurs prior to the landing of any marine forces. The objective of preemptive shelling is to reduce the capabilities of enemy shoreline defenses by bombarding defense positions. This bombardment is scheduled and directed by naval forces. The schedule is static; it does not change once the phase commences. Successful execution in the preemptive shelling phase will increase the probability of success in the second phase, which we call **assault support**. The transition to the assault support phase occurs when marine forces land and take their initial positions. The assault support phase is characterized by the continual receipt of requests for bombardment of specific shore defense positions. Calls for assault support shelling are made by the landed force and supported by spotters stationed near the targets. These calls for support shelling arrive intermittently and are serviced based on the priority of the call and the destructive power of the target.

2.1 MAJOR CALIBER AMMUNITION

Consider a single round of major caliber ammunition. It is comprised of a small number of major components, including fuses, primers, propellant igniters, propellant, propellant casing, case plug, projectile, and explosive. Each of these major components is in turn an assembly of a number of subcomponents.

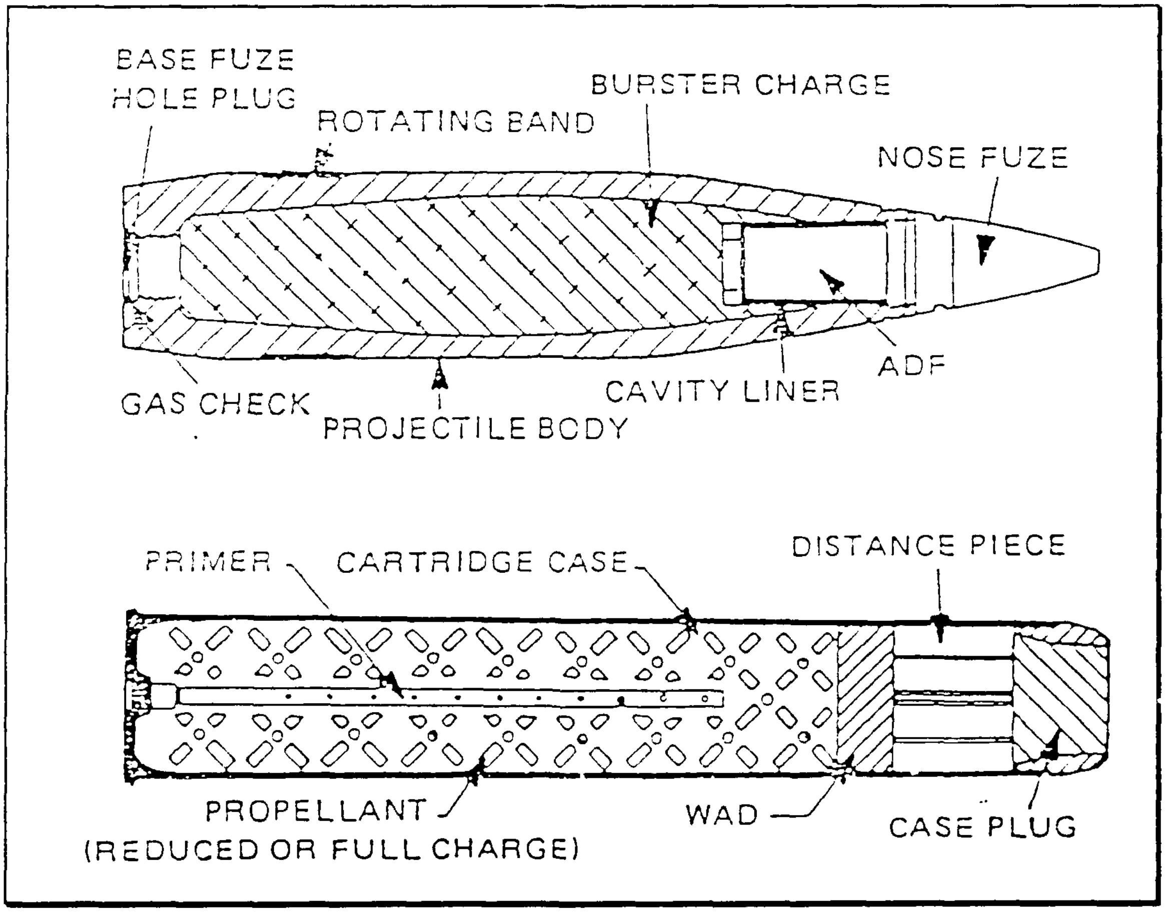

Figure 2.1. 5-Inch, 54-Caliber Propelling Charge and Projectile

The key functional characteristic of this system is its strictly serial operation. For example, a typical detonating train consists of a chain of stages

intended to increase the fuze signal energy level to a degree sufficient to detonate the explosive payload. The output signal of the sensing equipment (radar signal, acoustic impulses, hydrostatic pressure, etc.) is sent to a primer. This device converts electrical or mechanical energy into explosive energy. Although this energy is minimal, it suffices to trigger an auxiliary detonator. Following this, the output power of the auxiliary detonator triggers a chain of insensitive explosives in the booster stage until detonation of the payload occurs. (See *Weapons Systems Fundamentals*, NAVORD OP 3000 Vol. 2, First Revision, for details.) Then for example, if the primer fails, no other component down the chain will have a chance to operate. It is this simple serial structure that greatly simplifies the analysis of the possible failure modes induced by the system, as it will be seen in the following subsection.

2.2 FAILURES

We will continue now with a structural analysis of the common modes of failure of the single gun round system. We will consider a round to be effective if it gets out of the barrel, hits the target and detonates successfully. Otherwise, if any of these conditions is not satisfied, the round will be labelled as non-effective. There are two operationally distinct failure classes, namely, **interruptive failures** and **non-interruptive failures**. We will assume that there is a total of N different types of failures with type F_1 through type F_{N-1} corresponding to interruptive failures and type F_N corresponding to a non-interruptive failure.

An interruptive failure of type i (F_i, $i = 1, ..., N$-1) is caused by a malfunction of the round, the gun, or the crew, which causes the gun to stop

firing for some time T_i. Examples of interruptive failures are firing pin failures, or failures in the propellant chain. An interruptive failure causes the system to stop firing for some time T_i in order to fix the problem, after which the system performs as before.

A non-interruptive failure occurs when the round is successfully fired from a gun barrel but fails to cause effective damage to the target. Causes for this might be a faulty or incorrectly set variable time fuse, insufficient initial velocity, guidance errors, faulty detonation or even targeting errors caused by the crew. Although no effective damage is done to the target, a non-interruptive failure does not affect the gun in any other way, i.e., a non-interruptive failure does not affect the future firing rate of the gun.

For the current analysis we have assumed that T_i, $i = 1, \ldots, N$ are known and deterministic values. (We plan to extend this work to include randomly distributed repair times). We will also *normalize these values according to* the firing rate of the gun, i.e., if the gun is firing at 18 rounds/minute, we then measure T_i in units of 1/18 minutes. In this manner the down times caused by each particular failure will be weighted proportionally to the firing rate of the gun, so that a 10-minute interruption is considered *worse* for a gun shooting at a high firing rate than a gun shooting at a lower rate. This also implies that an effective round and a non-interruptive failure each take one unit of time.

Consider again a single round of a major caliber ammunition. The linear nature of this system allows us to model the system so that the lower levels of failure take precedence over the higher levels. Then, the failure (conditional) probabilities that can be estimated by observation are given by

$$x_1 = P[F_1 \text{ occurs}]$$

$$x_i = P[F_i \text{ occurs} \mid \text{no } F_j \text{ occurred for } j < i],$$

for $i = 2, \ldots, N$. Hence, the probabilities of the different failure types may be computed as

$$q_i = P[F_i \text{ occurs}]$$

$$q_i = P[F_i \text{ occurs and no } F_j \text{ occurs for } j < i].$$

By the way we have defined the observed conditional probabilities (x_i's) the failure types are independent and therefore

$$q_i = x_i \prod_{j<i} (1 - x_j) \tag{2.1}$$

for $i = 1, \ldots, N$. Thus, the q_i values will allow us to compute the reliability measure for the single gun-round system.

2.3 A MEASURE OF PERFORMANCE OF THE GUN-ROUND SYSTEM

We now present a measure of performance of the gun-round system based on the time required to deliver an effective round on the target. Recall that a round is considered effective upon successful detonation on the target. Let the random variable T_p represent such time measured in firing epochs, then

$$T_p = \sum_{i=1}^{N} [P_i T_i] + 1 \tag{2.2}$$

where P_i is the number of failures of type i occurring between effectively delivered rounds, i.e., the P_i's are geometric random variables with parameter $p_i = 1 - q_i$, for $i = 1, ..., N$. Thus, the first two moments of T_p are given by

$$E\left[T_p\right] = \sum_{i=1}^{N} T_i(1-p_i) / p_i + 1; \tag{2.3}$$

$$\mathrm{var}\left[T_p\right] = \sum_{i=1}^{N} T_i^2(1-p_i)p_i^2. \tag{2.4}$$

There is a very important relationship between these two moments that serves to consolidate our objectives, namely, monotonicity. As it will be seen in the following theorem, the expected value and the variance of the random variable T_p increase and decrease together. In evaluating the performance of a given set of components with associated x_i values, low variance of T_p is desirable as well as low expected value. This theorem guarantees that components giving lowest expected time between effective rounds also give the lowest variance. Thus, we are interested in decreased values of both $E[T_p]$ and $\mathrm{var}[T_p]$, and these goals do not conflict in any way.

THEOREM 2.1. Given two alternatives p and $\bar{p}$ in $[0, 1]^N$, if $E\left[T_p\right] < E\left[T_{\bar{p}}\right]$, then $\mathrm{var}\left[T_p\right] < \mathrm{var}\left[T_{\bar{p}}\right]$.

PROOF. We will show that for two points p and $\bar{p}$ suitably close to one another, that $\nabla E\left[T_p\right]^T (p - \bar{p})$ and $\nabla \mathrm{var}\left[T_p\right]^T (p - \bar{p})$ have the same sign. Thus, descent directions for $E\left[T_p\right]$ are also descent directions for $\mathrm{var}\left[T_p\right]$. Consider the product

$$
\nabla E\left[T_p\right]^T (p-\overline{p})^T \nabla \operatorname{var}\left(T_p\right)^T (p-\overline{p})
$$

$$
= (p-\overline{p})^T \nabla E\left[T_p\right] \nabla \operatorname{var}\left(T_p\right)^T (p-\overline{p})
$$

$$
= (p-\overline{p})^T \begin{bmatrix} -T_1 \cdot p_1^2 \\ \\ \vdots \\ \\ -T_N / p_N^2 \end{bmatrix} \left[(p_1-2)T_1^2 / p_1^3, \cdots, (p_N-2)T_N^2 / p_N^3\right](p-\overline{p})
$$

$$
= (p-\overline{p})^T \begin{bmatrix} (2-p_1)T_1^3 / p_1^5 & (2-p_1)T_1^2 T_2 / p_1^3 p_2^2 & (2-p_1)T_1^2 T_3 / p_1^3 p_3^2 & \cdots & (2-p_1)T_1^2 T_N / p_1^3 p_N^2 \\ (2-p_2)T_2^3 / p_2^5 p_1^2 & (2-p_2)T_2^3 / p_2^5 & (2-p_2)T_2^2 T_3 / p_2^3 p_3^2 & & (2-p_2)T_2^2 T_N / p_2^3 p_N^2 \\ (2-p_3)T_3^3 / p_3^5 p_1^2 & (2-p_3)T_3^2 T_2 / p_3^3 p_2^2 & (2-p_3)T_3^3 / p_3^5 & & \vdots \\ \vdots & & & \ddots & \vdots \\ (2-p_N)T_N^3 / p_N^5 p_1^2 & \cdots & & & (2-p_N)T_N^3 / p_N^5 \end{bmatrix} (p-\overline{p})
$$

$$
= (p-\overline{p})^T A (p-\overline{p}) \tag{2.5}
$$

which is a quadratic form in the matrix A. It is simple to determine that A is positive semi-definite. This tells us that

$$
\left[\nabla E\left[T_p\right]^T (p-\overline{p})\right]^T \left[\nabla \operatorname{var}\left(T_p\right)^T (p-\overline{p})\right] \geq 0 \tag{2.6}
$$

for any vector $(p-\overline{p})$. Hence, we may conclude that in a suitably small neighborhood of any point p, descent directions for $E\left[T_p\right]$ are also descent directions for $\operatorname{var}\left[T_p\right]$. □

Backed by the results of the above theorem we can now define a measure of performance of the gun-round system as:

$$
ef = 1 / E\left(T_p\right) = \text{ round efficiency.} \tag{2.7}
$$

This quantity represents the number of effective rounds per unit time (again measured in firing epochs). As will be seen in the following section the

simulation results confirm that *ef* represents a good measure of performance of the naval gunfire support system, highly correlated with both the destruction time of the target and the destructive power left by time *t*.

Example 1

Eight failure types known to cause a preponderance of the failures experienced by a naval gun are given below in Table 2.1 along with their interruption (repair) times. These times were derived from studying the figure "Hot Gun Misfire Procedures and Safety Time Schedule for 5-inch, 54-caliber Guns Mark 45 Mods 0 and 1". Failure type descriptions are given in Table 2.2, with some symptom information, remedy, and the interruption time for each. When two numbers are provided they are for hot and cold gun situations. Repair of these types of failures on a hot gun require that the gun be cooled for 30 minutes before repair can begin. This assumes that an automatic internal cooling system can be employed. The wait is two hours with no cooling system. Finally we evaluate the efficiency of a round under these conditions.

TABLE 2.1

Failure Type	Description	Data Status
1	Loader Microswitch Fails	E
2	Firing Circuit Fails	E
3	Breachblock Closed	E
4	Firing Pin Fails	E
5	Propellant Primer Fails	D
6	Propellant Impurity	D
7	Fuse Fails or is Missed	D
8	Detonation Train Fails	D

The qualifier data status is E if the probability of failure must be estimated from data provided from a gun failure data base, while those with data status D are failure types whose probabilities are variable, open to decision.

TABLE 2.2

F_i	Description/Symptom	Remedy	T_i	p_i
1	Round jammed, loader stops	Mechanically unjam	25/55	0.05
2,3	Electronic failure in system	Isolate and replace component	1.5	0.1
4	Electronics work but no fires occur	e.g., Replace pin	21/51	0.02
5	Propellant will not fire though mechanical firing sequence occurs	Eject propellant casing and fire clearing round	10	0.03
6,7,8	Non-interruptive failure	Shoot again	1/firing rate	0.01

Based on the above data and the equations provided in the previous subsection we evaluated the efficiency of the round for a gun shooting at 20 rounds/minute and obtained $ef = 0.16$, i.e., 16% of each round is effective. In other words, if we assume that 10 rounds are necessary to destroy the target, then given $ef = 0.16$, we will need an average of 62.5 firing epochs to deliver 10 effective rounds.

2.4 PURPOSE OF ef

As it will be seen in the following section, the simulation model (and the associated computer program) will allow us to determine the appropriate value of ef in order to meet battle goals with respect to the time required to destroy all targets, the casualty rate, destructive power left by time D, etc. The

selected number for ef, say ef^*, will thus represent a global measure to be satisfied by all types of ammunition and guns in the system, ensuring in this way that the battle objectives will be met.

It should be noted that many individual components are either common to different guns or to different ammunitions, e.g., two different models of the same type of gun may share the same firing circuit. Therefore, the decision as to what the minimum reliability requirements are for all the components in the system should be taken globally, i.e., the result of a model that includes all guns and all ammunitions simultaneously. In other words, each different round of ammunition and each gun in the system will have to satisfy an equation of the type $E[T_p] \leq 1/ef^*$.

A system like the one described above possesses an infinite number of solutions. It is possible, in order to simplify the selection of a particular solution, to include an objective function, e.g., minimum procurement cost. This last step is dependent upon knowledge of the different costs associated with buying components of different reliabilities, information that we understand may not be readily available to the decision maker.

3. SIMULATION MODEL

We have developed a simulation model to estimate the relationship between *ef* and other standard performance measures which include mission duration, average casualty rate over mission lifetime, and the percentage of opponent destructive power disabled at arbitrary time D. The model took the following aspects into account:

i) gun reliability
ii) spotting,
iii) targets and target hardness,
iv) navigation error,
v) guidance error,
vi) fluctuation in initial velocity
vii) ships and guns and dependence, and
viii) all possible JMEMS data.

The goal of the simulation model was not to simulate a particular known engagement, but to give decision makers a feel for the impact of varying *ef* values in terms they are used to considering (standard performance measures). The simulation results show that *ef* explains nearly all variability in observations of the percentage of targets destroyed at arbitrary time D, the time required to destroy all the targets, and the casualty rate.

The simulation will also provide the decision maker with the statistical properties of these measures. Thus the decision maker has the ability to measure reliability performance and compare previously incomparable component configurations.

The decisions he will make involve procurement and surveillance. In procurement decisions, he will specify reliability values which meet minimum requirements for *ef*, and which are most economical. In surveillance, disassembled rounds will be tested piece by piece. If the round still is within the minimum *ef* standard, it is still mission effective. If not, the rework required to bring it to mission effective status can be prescribed in a cost-effective way. Thus the critical value of *ef* must be established.

3.1 THE MODEL

The model is designed to mimic the spotting, communication, targeting, and destruction aspects of the NGFS system. The system consists of several ships, each equipped with one or more naval guns. These guns are tasked to prosecute and destroy a prespecified set of targets by a specified time. Interfering with the gunfire are inaccuracies in the fall of shot, inaccuracies in the ship's internal navigation system, gun system interruptions and failures, and ammunition failures. We now describe the simulated processes in more detail.

3.1.1 The Target List

The specified targets reside on a target list which gives each target's type, the lethality points for the targets, and each target's field of view. The target type is referenced to a target type list which gives detailed information on the method of engagement for the target type. An example of a target type may be a TEL of an antiaircraft gun, while a target might be a particular TEL in a particular location.

Point values are assigned to each of the targets to control the manner in which they are engaged. Generally speaking, targets are engaged in a highest-points-first regime, with exceptions made for partially destroyed targets.

When the NGFS scenario begins, the targets with the highest point values are taken from the target list and engaged, one target per gun. Each target is prosecuted until it is destroyed, or until the gun engaging it suffers a severe casualty. If the target is disengaged and not destroyed, it is returned to the target list in its current state of damage. The scenario is not considered complete until all targets on the list have been destroyed.

3.1.2 Spotting

Each target is first engaged by using a bracketing method for spotting the rounds. The brackets are established as shown in Figure 3.1. Two points are established behind (P_L for P_{LONG}) and in front of (P_S for P_{SHORT}) the target. Around each point, a box is established. The evolution starts as the ship attempts to place a round in Box L, X_L is an acceptable long spotting round. Then, the ship attempts to place a round in the short box, say at X_S. The distance from P_L or P_S to the target, and the width and length of the spotting boxes are specified for each target type. Note that if the distance from P_S to the target is specified as 0.0, the gun performs single-shot spotting on the target.

The preceding description fits the actions of a ship engaging its first target. If, however, the ship has just destroyed an adjacent target, this bracket procedure may be overly cautious and time consuming. Hence, if the ship immediately engages a target within the same field of view as the target just destroyed, the ship performs single-shot spotting instead of the bracketing procedure.

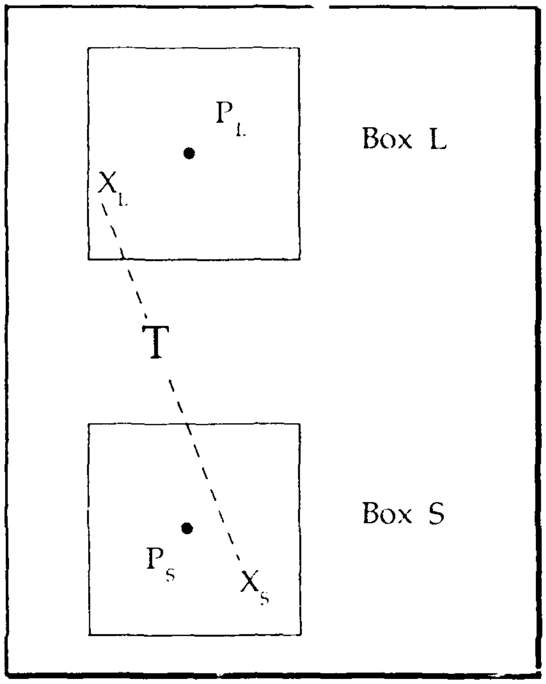

Figure 3.1. Target Spotting

3.1.3 Firing for Effect (FFE)

Once adequate spotting has been performed, the ship will fire for effect on the target. This involves firing at a position exactly between the two spotting locations, as at the last single-shot spotting location. The gun fires a salvo the size of which is specified by the target type, each round following the previous one by a delay equal to the specified cycle time of the gun.

3.1.4 Destruction

The combination of the impact point, the round type, and the target type allows us to specify the amount of damage done to the target. Each round-target type gives us an effective casualty radius (ECR) within which some damage to the target can be expected. Each target type has a specified number of lifepoints, and a number of points it loses if the round lands within the ECR and fuses successfully called hitpoints. We further downgrade the

effectiveness of the round by a probability of damage, which is conditioned on the round landing within the ECR and fusing. Between the hitpoints, lifepoints, and this conditional probability, the analyst has significant modeling flexibility. When a target's lifepoints are no longer positive, it is destroyed.

3.1.5 Battle Damage Assessment

After an effect salvo is fired, there is a delay before the disposition of the engaged target is known to the ship. Contingent upon the condition of the target, the ship may do one of three things. If the target is unharmed, the ship attempts to respot the target; if the target is damaged but not destroyed, the ship fires another salvo for effect; if the target is destroyed, the ship engages a new target.

3.1.6 Navigation Error and Registration Rounds

Prior to attempting to spot its first target, each ship experiences some error in its navigation solution as well as some gun-system bias. These two effects conspire to make the gun system less accurate. It is a common practice to fire several registration rounds at a point outside the target field, and to track the landing point of these targets using the ship's radar. From this data we form an estimate of the bias carried by the ship's navigation system so that future firings are more accurate.

3.1.7 Found Aimpoints and Spotting Inaccuracies

When the ship fires a round, it does so at a specified aimpoint (x_A,y_A) given in (x,y) coordinates. The round, due to several exogenous conditions, lands at some nearby point (x_I,y_I). In our model, we assume that the difference between (x_A,y_A) and (x_I,y_I) is a bivariate normal random variable.

With mean (0, 0) and variance which is specified in the data set. Each gun is allowed a different variance, and each round type may magnify this inaccuracy as appropriate.

When a spotter observes the impact point relative to the target, he advises the ship to adjust the aimpoint by the *observed* error, as opposed to the aimpoint's inaccuracy. See Figure 3.2.

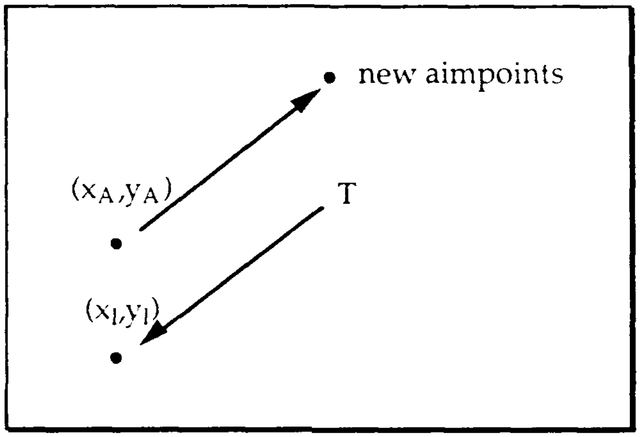

Figure 3.2. Aimpoint Adjustment

This process continues until the *impact* point satisfies the spotting criteria.

3.2 GUN AND ROUND FAILURES

Of primary interest in this research is the effect that gun system and ammunition failures have upon the overall performance of the NGFS system. As discussed above, the system experiences failures which are of two distinct types, these being **interruptive** and **noninterruptive** failures. Each failure is modeled to occur with a given probability of each firing of the gun, and each failure is assumed to be independent of all previous firings. Furthermore, the observation of failures is hierarchical, so that the occurrence of a failure masks occurrences of failures of components further

down the detonation train. Upon recovery from a failure, the system is assumed good-as-new.

3.2.1 Noninterruptive failures

Modeling noninterruptive failures is quite straightforward. If one of these failures occurs during the spotting process, the round is assumed to be unobserved by the spotter. Hence, the spotter will require that an additional spotting round be fired at the current spotting aimpoint. During the FFE phase of the mission, the round is simply ineligible to inflict damage upon the target.

3.2.2 Interruptive failures

The duration of an interruptive failure changes depending on whether the gun is hot or not. Upon an interruptive failure during either phase of a mission, there is a possibility that the gun should be taken off-line to be repaired, and the engaged target should be made available to other guns. This target release evolution occurs when the gun is expected to be down for more than TOO LONG time units. The target becomes reengageable by another gun after RELEASE TIME units. The values of TOO LONG and RELEASE TIME are specified in the scenario.

If the failure is not severe enough to release the target, the actions of the system depend on the mission phase at the time of failure. If spotting is interrupted by a failure, the spotting resumes by firing at the original spotting location. If the gun is firing for effect, the resumption of firing involves shooting the entire salvo over again. However, when FFE is interrupted it is possible that the target has already been destroyed. Thus, BDA is done upon

every interruption of an FFE. An interruption of an FFE could, in this manner, result in reassigning the failed gun to a new target upon recovery.

3.3 DATA FILE PRODUCTION

The generation of data for the model falls into three general areas. First is the collection and evaluation of scenarios. Second is the translation of known targets to JMEMS targets and the evaluation of munitions effects. Third is the evaluation of gun system reliability. All of this data is destined for the scenario data file of the simulation AMMO.

3.3.1 Collection and Evaluation of Scenarios

There were three scenarios considered for use in the study, based on amphibious actions in the Middle East, northern Europe, and the northern Pacific. The Mideast scenario is a helo-borne landing and therefore does not meet the requirements of the study. The Northern Europe scenario is an unopposed landing and, thus, does not meet the requirements of this study either. The third scenario was a northern Pacific scenario with many targets designated to be assigned to prelaunch strikes by naval air and naval gun assets. Specifically 18 targets were evaluated as being assigned to NGFS. The NGFS time window for these targets is the 48 hours preceding the scheduled landing time. We used this scenario as the basis of our model runs.

Specific detail about the targets other than location, elevation and general nomenclature was not available, therefore assumptions had to be made about the targets. It was assumed, for example, that AA battalion headquarters would be fortified in such a manner as to present the damage profile of an armored personnel carrier. It was assumed that each surface-to-air missile

battery had eight surface-to-air missiles. It was also assumed that an aviation regiment would be comprised of eight aircraft. With regard to the navigational error, it was assumed that beacons were set in place on the beach for geographical reference and aid in navigation. Ships were assumed to be able to maneuver, gain, and maintain, a range of 12,000 yards to each target as it was taken under fire.

3.3.2 Target Translation

The scenario generated the following target type list:

EW SITE
SW SITE
GCI SITE
AA BATTALION HEADQUARTERS
AA BATTERY
HELO SQUADRON
SAM BATTERY
SAM BATTALION HEADQUARTERS
AVIATION FIGHTER SQUADRON

The JMEMS target list considered was as follows:

140MM ROCKET AND LAUNCHER
FROG 4 ROCKET
152MM FIELD GUN
ZIL 157 TRUCK
SEPAL CRUISE MISSILE
CROSS SLOT RADAR
FROG 7B ROCKET POINT AND AREA TARGETS
BMP ARMORED INFANTRY VEHICLE
PERSONNEL TARGETS

For the target translation, EW, GCI, and SW sites were considered to be predominantly antenna arrays and electronics equipment, therefore they translated to CROSS SLOT radar for obtaining input data for the simulation

from the JMEMS publications. HQs translated to hardened targets with a larger target radius than most hard targets. AA battery translated to a 152MM field gun. Helo and aviation squadrons translated to sepal cruise missiles. SAM battery translated to FROG 4 rocket.

From this translation we were able to generate the target type list in the data file described in Section 4.

3.3.3 Gun System Reliability

The 5-inch Gun Mount has 53 reliability blocks which are all in series. A reliability block diagram is a model of a system or operational mode, broken down to a level in which all components in each block are either all energized or all nonenergized at any point in time (NAVSEAINST 3500.1A Advance Draft). Reliability block diagrams (RBD) are used by the Fleet Analysis Center to determine reliability measurements of Navy ship systems. The RBDs for a particular system were developed by the engineering and maintenance support activities at the direction of the cognizant system program manager.

The OPNAV 4798/2K is the primary source for the Material Readiness Data Base (MRDB) In addition the MRDB is augmented with casualty report messages, employment tapes, and other supplementary data sources. Data collected from the start of the data base in January 1984 until August 1986 includes information from the NAVSEA Non-expendable Shipboard Equipment Status Logs, form 4855/2, which are no longer required. Data from 1984 to 1986 was used because it includes the equipment status log information. It is a source of continuous real time observation and actual clock readings. The mean time between failures (MTBF) and the mean time

to repair (MTTR) were obtained for each of the 53 RBD's from the MRDB. The RBD MTBFs and MTTRs were used instead of the system reliability to avoid the data base scenario adjustments of system reliability that are made using a demand factor for each of the RBDs based on the percentage of time it is energized during a typical mission life normalized by a ratio of energized time to real clock time, aggregated over all units reporting. We wanted to use as pure a number as possible and therefore modeled the individual 53 RBDs in the simulation and used the unadjusted data from the 1984 to 1986 time frame.

3.3.4 Data Collection Postmortem

There is a mismatch between those targets that we are describing in our scenarios and the information about the specific effect of our ammunition on targets that we were able to develop at this time. We are in the process of getting the effects data needed from the JMEM Munition Effects Working Group. Our scenarios should be generated with the same level of granularity or scale as the JMEMS publications, so that translation, if required, can be done in reasonable fashion. In terms of our own systems, there needs to be a methodical way to collect information in order to support reliability calculations, and to do so in such a way as to isolate those periods of time when the systems are specifically in a mission state. It does no good for us to evaluate our systems at 90 percent reliability, lets say, according to the data base when the system does not work 50 percent of the time while it is on the firing line. System reliability for a mission may not be accurate for the mark 45 mod 1 system because the collected data is based on clock time, not mission time.

Because of these factors, it was deemed valuable that NGFS be observed so that some idea of validation of the model could be obtained. The observation of one ship does not suffice to validate the simulation model, but it did not invalidate the model. It was encouraging to see that the rate of fire of the ship in actual clock time was similar to that predicted by the model. It was also encouraging to see the gun perform as well as it did as the ship's crew became acclimated to the environment of NGFS.

4.0 RUNNING THE SIMULATION

In this section, we describe the data files required to operate the simulation model, and the output attainable.

4.1 DATA FILES

There are two data files required to run the simulation AMMO. These files are known as the *scenario* and *run control* files. The scenario file, an example of which is shown in Figure 4.1, contains three distinct sections: timing information, target description information, and ship-gun-round system description information. Finally, there is a list of seeds used in the simulation.

All of the data collected from the FLTTAC, JMEMS, and other sources is destined for the scenario data file. The scenario supplied by NWSC was used to choose the targets and target types, and to specify the numbers of ships and guns. In addition, the data on the timing and accuracy of the gun system was provided by rough estimates from data collected aboard the USS Ainsworth.

TIMING INFORMATION

5.5	bdatim, the time (in min.) it takes to do BDA
3.5	spttim, the time between spotting round
2	numgun, the number of guns in the scenario
1	numshp, the number of ships in the scenario
2	numshl, the number of shell types used in the scenario
4	numtgt, the number of targets
2	numtty, the number of target types
100.	dtime, the time of the amphibious assault
1	dswtch, 1 means the simulation stops at dtime, 0 means destroy all targets
4	regrnd, number of registration rounds each ship shoots at the beginning of each scenario

TARGETS—id tgttyp points fov (one for each target)

one	1	100	1
two	1	99	2
three	2	45	1
four	2	56	2

TARGET TYPES—id, shltyp, lifpts, hitpts, effect, ecr, deflct, jmemsp, ecrlng, pcorct, blng, bwd

type 1	1	10	3	5	50	20	0.90	1	1.0	1.5	1.0
type 2	1	10	3	5	50	20	0.90	1	1.0	1.5	1.0

SHIPS—ship nav error sigshp (., 1) sigshp(., 2)

100.0 100.0 standard errors, x and y, of the ship nav system

GUNS—ship, gnumf, hotrnd, siggun(., 1), siggun(., 2), cycle (one per gun)
gfailp, gfailt(cold, hot) (one per failure mode of the gun)

1	2	10	20.0	60.0	0.05
0.05	1.0	2.0			
0.10	0.0	0.0			
1	2	10	20.0	60.0	0.05
0.05	1.0	2.0			
0.10	0.0	0.0			

SHELLS—snumf, sigshl(., 1), sigshl(., 2) (one per shell type)
sfailp, sfailt(hot and cold) (one per shell failure mode)

4	1.0	20.0
0.5	5.0	10.0
0.01	0.0	0.0
0.03	3.0	3.0
0.002	4.0	14.0
3	1.0	0.0
0.01	0.0	0.0
0.03	3.0	3.0
0.002	4.0	14.0

Figure 4.1. Scenario Data

The blocks of data pertaining to the guns and shells may be nonintuitive in their design. The first line for each gun description gives, in order, the ship on which the gun is mounted, the number of failure types for the gun, the number of rounds fired before the gun is considered hot, the standard errors of the dispersion of shot for the gun (x and y), and the time between rounds fired for effect for the gun. The next several lines of data are the probability of occurrence and the recovery times (cold and hot) for each failure type.

The blocks of data pertaining to the shell types are structured similarly. The first line gives the number of failures for the shell type, followed by the additional dispersion caused by the round. The following lines give the probability of occurrence, and the recovery time (cold and hot) for each failure type.

A second file, the run control data file, contains some simple information used to limit the runs of the simulation and to implement our experimental design. An example of the run control file is given in Figure 4.2. The run control file specifies the maximum duration of any single simulation run, MAXTIME, the level of accuracy required of each of the performance measures, PCT, and the maximum number of replications a given experiment is allowed to run, MAXREPS. For example, if MAXREPS is 200 and PCT is 0.05, then the simulation experiment will stop when

1) the confidence interval half width is less than 5% of the mean for each performance measure, or
2) 200 replications have been completed.

Lines 4-6 of the file concern the "scrunching" of ECR values. As has been mentioned in the discussion of JMEMS data, it was often seen that a given

round-target pair would have an effective casualty radius of 850 meters and a probability of destruction of 0.01. We found this unreasonable and devised a crude way to make the probability of destruction increase by insisting on more accuracy in round delivery.

200		MAXREP
35,000.00		T
0.15		PCT
F		T TO MODIFY THE DISKS, F TO SKIP THAT PORTION
40.0		R (= ADAPTIVE RADIUS WE USE TO SCRUNCH ECRS)
1	0.000	0.0005
1	0.00	0.004
1	0.00	0.01
1	0.00	0.004
1	0.000	0.002

Figure 4.2. Run Control File

We made the assertion that, within limits, ECR $\times$ Pr[destruct] = C for some constant C corresponding to the firepower of the round against the target. The aforementioned limits are established in lines 4 and 5 of the data. R gives the minimum ECR value for any round-target combination, while PMAX gives the maximum Pr[destruction]. The program, when instructed, will attempt to concentrate firepower until one of these bounds becomes tight. Experimentally, we have found that the simulation predicted highest gun efficiency when R was equal to the round dispersion standard error given in the scenario data file.

The last several lines give the experimental design, which is of the complete factorial type. We are interested in the behavior of each of our performance measures when the probabilities of failure of each of the round components are varied. By convention, we vary the probability of failure for

round type 1 in the experiment. If the scenario involves several round types, the user should manipulate the scenario data file so that round type 1 is the round of primary interest for the run.

The design is given by the number of levels, the lower limit, and the upper limit of the probability of failure for each failure type for round type 1. Thus, if the line corresponding to failure type 1 in the run control file is given as

3   0.01   0.03,

then type 1 failure probabilities will vary over the set {0.01, 0.02, 0.03}. If the number of levels for a failure type is given as 1, the probability of failure reverts to that found in the scenario data file.

4.2 Model Responses

When the model runs, the user's screen is notified of the number of experiments that will be performed in the run, the number completed thus far, and the number of replications finished for the current experiment. Upon completion of each experiment, the user is notified of the number of replications of the experiment which were *censored* because the targets were not all destroyed before MAXTIME. The number of censored runs should be small (ideally 0!) for each experiment. If this number becomes a significant portion of the sample size for the experiment, the values of the scenario, failure, or MAXTIME, should be reconsidered.

When the simulation does run successfully, the output is given in the form shown in Figure 4.3. Estimates of the primary measures of performance, the mean scenario completion time, the time average of the

```
KEEPON = F              0 OF          10REPS CENSORED

THE NUMBER OF REPLICATIONS REQUIRED WAS             10

        THE AVERAGE MISSION LIFETIME =                   563.5317
                VARIANCE OF THE MEAN =                  1146.4990
      STANDARD DEVIATION OF THE MEAN =                    33.8600

    THE TIME AVG OF THE TARGET VALUE =                    77.2558
                VARIANCE OF THE MEAN =                    23.3675
      STANDARD DEVIATION OF THE MEAN =                     4.8340

 ROUNDS PER MINUTE BY GUN
   1        1.289   WITH STD ERROR       .146
   2        1.612   WITH STD ERROR       .101
   3        1.326   WITH STD ERROR       .148
   4        1.387   WITH STD ERROR       .124
   5        1.338   WITH STD ERROR       .120
   6        1.722   WITH STD ERROR       .149
 THE GLOBAL AVERAGE
            1.446   WITH STD ERROR       .059

  THE AVG % OF TARGETS DEAD AT DTIME =                     1.0000
                VARIANCE OF THE MEAN =                      .0000
      STANDARD DEVIATION OF THE MEAN =                      .0000

  THE AVG SURVIVING TGT VAL AT DTIME =                      .0000
                VARIANCE OF THE MEAN =                      .0000
      STANDARD DEVIATION OF THE MEAN =                      .0000

GUN    1          THE AVG ROUNDS PER MISSION =                    456.8999
                VARIANCE OF THE MEAN =                  2833.6540
      STANDARD DEVIATION OF THE MEAN =                    53.2321

GUN    2          THE AVG ROUNDS PER MISSION =                    473.2000
                VARIANCE OF THE MEAN =                  3422.3510
      STANDARD DEVIATION OF THE MEAN =                    58.5009

GUN    3          THE AVG ROUNDS PER MISSION =                    531.3000
                VARIANCE OF THE MEAN =                  3943.9120
      STANDARD DEVIATION OF THE MEAN =                    62.8006

GUN    4          THE AVG ROUNDS PER MISSION =                    440.3000
                VARIANCE OF THE MEAN =                  3836.4900
      STANDARD DEVIATION OF THE MEAN =                    61.9394

GUN    5          THE AVG ROUNDS PER MISSION =                    402.5000
                VARIANCE OF THE MEAN =                  4145.2280
      STANDARD DEVIATION OF THE MEAN =                    64.3834

GUN    6          THE AVG ROUNDS PER MISSION =                    487.2000
                VARIANCE OF THE MEAN =                  5527.7960
      STANDARD DEVIATION OF THE MEAN =                    74.3491
```

Figure 4.3. Example Output File

surviving target value, and the target value surviving at DTIME are prominently displayed. In addition, we report several sets of statistics concerning the experiences of each gun used. This report is generated by the program only when the number of experiments in the design equals 1. That is, only when a simple simulation run using the scenario data values is done. When there is more than one experiment in a design, the results are given in data files amenable to input in a graphical statistical analysis package such as GRAFSTAT.

5.0 DETERMINING RELIABILITY GOALS

In the previous sections, we have produced descriptions of the analytic reliability measure ef, and of the simulation analysis system. In the most fundamental terms, ef is a simple function of reliability measures of individual ammunition and gun system components. The simulation also uses the reliability data, as well as other system performance characteristics and an NGFS scenario as input. The output of the simulation is a set of battle goal results, as listed in Figure 4.3. Let us denote these k battle goal values by the vector $\mathbf{bg}(\mathbf{bg}_1, \mathbf{bg}_2, \ldots, \mathbf{bg}_k)$.

The reason for developing the simulation model is that components of **bg** have relevance and meaning to our prospective decision maker. Given a vector of battle goal results, we expect the decision maker to be able to determine if the performance of the system is acceptable. Pursuing this expectation, we compel the decision maker to specify a function

$$\Psi: \Re^k \rightarrow \{0,1\}$$

so that $\Psi(\mathbf{bg}) = 1$ if and only if the outcome **bg** is acceptable in terms of performance, $\Psi(\mathbf{bg}) = 0$ if not. For simplicity, we will assume that Ψ has the following form:

$$\Psi(\mathbf{bg}) = \begin{cases} 1 & \text{iff } \mathbf{bg}_i < \mathbf{bg}_i^* \quad i = 1, 2, \ldots, k \\ 0 & \text{otherwise.} \end{cases} \tag{5.1}$$

Hence $\mathbf{bg}^* = \left(\mathbf{bg}_1^*, \mathbf{bg}_2^*, \ldots, \mathbf{bg}_k^*\right)$ is the decision maker's **threshold performance vector.** Obviously some sign-switching will be necessary so that this threshold vector makes physical sense.

We propose that **bg** is a function,

$$\mathbf{bg}: [0,1] \rightarrow \Re^k$$

so that each battle goal is a function of ef, $\mathbf{bg}(ef) \in \Re^k$. Hence, we submit the following procedure for establishing reliability goals for major caliber ammunition components:

1. specify a set of N experimental reliabilities for each ammunition component for each round type.
2. specify $\mathbf{bg}^*$;
3. $i = 1, 2, \ldots, N$
   i. Calculate ef_i;
   ii. estimate $\mathbf{bg}(ef_i)$ via AMMO;
4. $ef^* = \min_i \left\{ ef_i : \Psi\left(\mathbf{bg}\left(ef_i\right)\right) = 1 \right\}$

The validity of the above procedure is based on the assumption that $\mathbf{bg}_i$ is nondecreasing in ef for each i.

Example 2.

From our preliminary analysis, we chose the battle goals as follows:

$\mathbf{bg}_1$ = total mission time;

$\mathbf{bg}_2$ = total firepower of threat at 1 hour after engagement begins

$\mathbf{bg}_3$ = time-integrated point value of targets

$\mathbf{bg}_4$ = percentage of targets left undestroyed at time of invasion, 48 hours after engagement begins.

Obviously the best of all possible situations is to have $\mathbf{bg} = [0,0,0,0]^T$.

We expect the decision maker to specify the threshold vector $\mathbf{bg}^*$ so that we can, in turn, provide a threshold ef^*. Obviously, lower values of the components of $\mathbf{bg}^*$ will face the value of ef^* up. The usefulness of ef^* is that it relates directly to gun and ammunition component failure probabilities.

5.1 ENHANCING EFFECTIVENESS

Given that the decision maker has specified a threshold level of performance **bg***, how must we deal with this threshold? For each round type, we are required to meet the attendant effectiveness threshold ef^*. The round types are considered to operate in a fixed environment, including the reliability performance of the gun system the round is used with. Thus, of all of the system component reliabilities that impact the calculation of ef for a round type, only the round component reliabilities are under our control.

Let us consider one round type with round components 1, 2, ..., k and exogenous components k + 1, k + 2, ..., N the exogenous components being those of the intended gun system. We hope to provide round to the fleet such that $p_1, p_2, \ldots, p_k$. The k probabilities of failure for each of the round components are small enough so that $ef^* \geq ef^*$. If this is not the case, then one or more of the component reliabilities must be improved in order for the round to conform to the specified reliability threshold.

The decision maker we allude to actually performs two roles, he procures ammunition components for assembly with currently held components to make new rounds, and he monitors the reliability of existing stockpiles of ammunition. When monitoring the stockpiles, he decides whether or not to perform some set of rework upon an ammunition lot to improve the reliability performance of the lot.

5.1.1 The Procurement Decision

For the procurement process, we will assume that the decision maker currently has in place procurement mechanisms for k–1 of the round

components, and has a high degree of confidence in the value of x_j, $j = 1, 2, \ldots, N$, $j \neq i$, the failure rates of the individual components. He needs a reliability goal for component i, that is, he needs to specify the maximum allowable x_i which will produce a round conforming to the overall reliability threshold.

From Section 2.3, we can state the reliability threshold constraint as

$$cf^* \leq \left[\sum_{j=1}^{N} T_j \left(1 - p_j\right) / p_j + 1 \right]^{-1}. \tag{5.2}$$

Isolating p_i, this constraint becomes

$$\frac{1}{A - 1} \leq p_i. \tag{5.3}$$

where A is given by

$$A = \left[\left(\frac{1}{cf^*} \right) - \left(\sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{T_i \left(1 - p_j\right)}{p_j} + 1 \right) \right] T_i^{-1}. \tag{5.4}$$

Tracing p_i to its origins as a function of the failure rate x_i, we arrive at the constraint

$$\left(1 - 1 / (A - 1)\right) \left(\prod_{j \neq i}^{N} \left(1 - x_j\right) \right) \geq x_i^*. \tag{5.5}$$

This is our reliability goal for component i.

We have related the constraint of the effectiveness of a round to the failure rate of the component to be procured. We recommend that acceptance

tests for the new component establish x_i^* as the upper control limit for the percent defective in all procured lots of component i.

Finally, if component i is to be used to build rounds of several different types, the reliability goal should be set by the round type establishing the lowest x_i^*.

5.1.2 The Surveillance Decision

Ammunition surveillance is the practice of removing several rounds from a stockpiled lot of ammunition and testing the rounds. This testing is done in two modes, these being total-system and component-wise. Currently, the acceptance criteria for pronouncing a stockpiled lot fleet-ready are ad hoc. We propose replacing the current surveillance test criteria with those that will ensure that the lot tested exceeds ef^* in efficiency.

Usually, only a subset of the components in a round are selected for component-wise surveillance testing. From the tests, we can easily establish an upper confidence limit on the value of x_i for each round component i which is tested.

Components that cannot or are not tested component-wise are tested in the total-system test. During the total system test, the number of failures which is interruptive should be counted and classified, so that upper control limits are established for p_i, the expected number of failures of type i which occur between successful rounds. Failures of types which are attributed to components tested component-wise are used to sharpen the estimates of the failure rates for these components.

Thus, after the initial surveillance tests, we will have an estimate of ef for the lot. If this estimate is above ef^*, we allow the lot to remain in the

stockpile and proclaim the lot to be conforming to our reliability goal. If the lot is not conforming, the decision maker has the option of replacing one or more of the components in each round in the lot. He has knowledge of the failure rate of the replacement components he has at hand, so he may determine whether performing the replacement will bring the lot into conformance with the reliability goal. No doubt, this rework decision has an economic aspect we do not address.

5.1.3 Evaluating Marginal Improvements

As we have developed ef as our performance measure, it is incumbent upon us to exploit the functional nature of ef to determine relationships between incremental improvements in reliability, training, or operations and fleet effectiveness in NGFS. We do this by taking partial derivatives.

Consider the following two equations;

$$\frac{\partial ef}{\partial T_i} = \frac{p_i - 1}{p_i} ef^2 \tag{5.6}$$

$$\frac{\partial ef}{\partial p_i} = \frac{T_i}{p_i} ef^2 \tag{5.7}$$

As $0 \le p_i, ef \le 1$, we know that $\partial ef/\partial T_i \in [-1,0]$, while $\partial ef/\partial p_i \in [0,1]$.

Equation 1 primarily addresses training of crew members, as better trained crews will shorten recovery times from gun or ammunition failures. Equation 1 tells us that the greatest operational payoff comes from reducing the recovery time of failures which occur most frequently, that is, with low values of p_i. Note further that Equation 1 does not explicitly involve T_i, so that we see clearly that frequency of failure is more important than severity.

Equation 2 tells us that incremental improvements in reliability of individual components are ordered by the ratio T_i/p_i. The greater this ratio, the more important an incremental improvement in x_i will be. Note that T_i/p_i is large when T_i is large and ...

x_i is large. The upshot of this discussion is that

i) crews should train with the goal of reducing the recovery time for the most frequent failures;

ii) contractors and procurement agents should weigh incremental improvements in component reliability using the ratio T_i/p_i.

Conclusion (ii) has direct impact on determining bonus values for contractors who exceed reliability specifications in their contracts.

5.2 Output Analysis

An experiment was designed whose purpose was to determine the functional relationship between each of the battle goals and the value of *ef*. The experiment consisted of three steps:

i) the simulation for K of different combinations of round component failure rates, executing M replications per combination;

ii) for each of the KM runs, exploit the difference between the observed value of *ef* and its known expectation to adjust the battle goal outcome for the run;

iii) develop a set of regression metamodels used to determine the functional relationship between each battle goal's expected value and the theoretical value of *ef*.

The experiment was performed for K = 34 and M = 200, using a stylization of a scenario provided by NWSC. The data used was perturbed from realistic values so as to avoid any classification constraints. In the following discussion, we will treat the following two battle goals,

i) $\mathbf{bg}_1$ = mean mission duration;

ii) $\mathbf{bg}_2$ = time average of enemy's firepower;

where firepower is given by each target's value, see Section 3.1.1. A direct relationship between the time average of the enemy's firepower and expected troop loss can be made if one (unrealistically) expects the amphibious assault to begin at the beginning of the scenario.

Figures 5.1 and 5.2 show the outcome of our experiment. In each figure, each datum represents the average response from the 200 runs of one failure rate combination, after adjustment as described in Step ii. This adjustment was performed using the linear control variate method, see Bratly, Fox, and Schrage [1983].

Briefly, this method consists of modifying each response from the simulation as

$$\tilde{Y}_i = y_i - \beta[ef_i - ef], \tag{5.8}$$

where Y_i is the i^{th} replication of the random variable Y, and ef_i is the i^{th} observation of the random variable EF. Since $E[EF - ef] = 0$, we have $E[\tilde{Y}] = E[Y_i]$ for each i. it is well known that the best choice of β is given by

$$\operatorname{cov}[EF, Y]\frac{\operatorname{var}[Y]}{\operatorname{var}[EF]}. \tag{5.9}$$

as we don't know the value of β, we estimate the required quantities from each of the K experimental combinations of failure rates. These estimates are shown graphically in Figure 5.3. Figure 5.4 graphically illustrates the reduction in variance in the mean response of each of the experimental combinations for the time-averaged fire power battle goal. The reductions in variance are in the neighborhood of 40–50% for this battle goal. Thus, by exploiting the difference between the simulation's experimental outcome for

ef and the true expected value, we have made our procedure 40–50% more efficient.

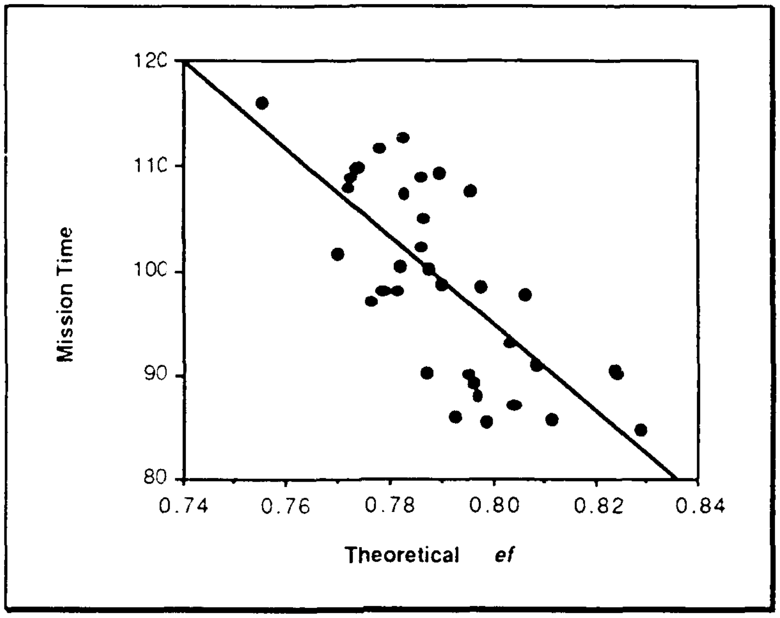

Figure 5.1. Battle Goal 1 Plotted as a Function of Theoretical *ef*

For the two battle goals, we see the fit of the two regression metamodels we constructed using standard techniques, see Kleijnen [1975]. Our estimates of the linear relationship between *ef* and each of the battle goals is given as

$$\mathbf{bg}_1 = 427.62 - 415.79\, ef \tag{5.10}$$

$$\mathbf{bg}_2 = 1693.2 - 1069.4\, ef \tag{5.11}$$

Both fits were subjected to standard regression diagnostics, and both were determined to be acceptable.

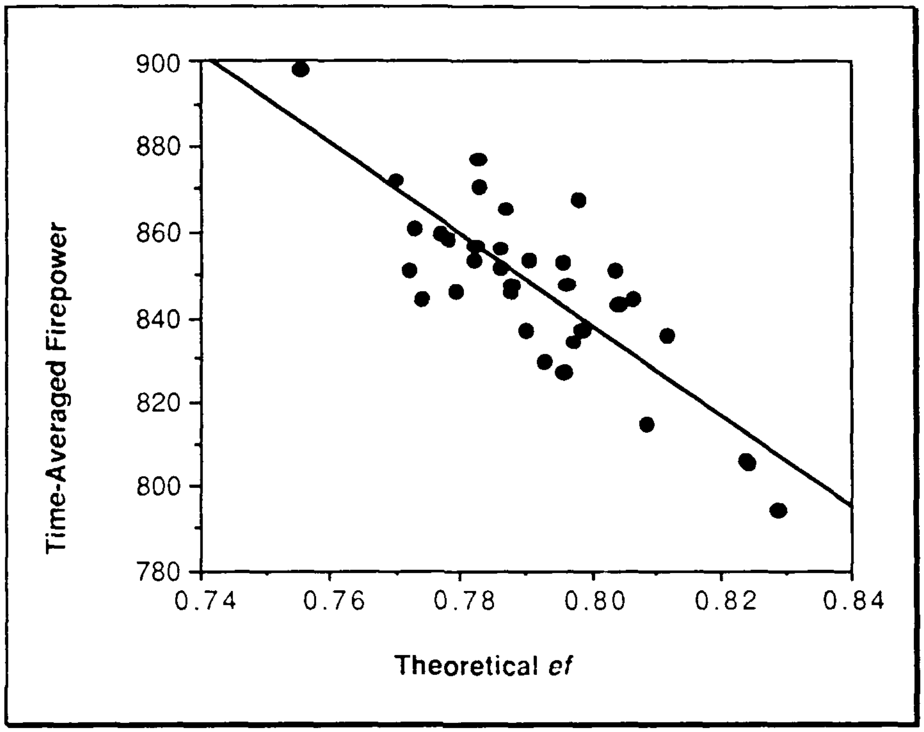

Figure 5.2. Battle Goal 2 Plotted as a Function of Theoretical *ef*

It is worth noting that with our combination of variance reduction technique and linear metamodel, we are regressing our battle goal outcomes on the quantities $ef_i - ef$ and ef, and that these two calculations are pursued for very different ends.

Setting Reliability Goals, an Example

Suppose that the decision maker makes the determination that for the targets and scenario described, that the battle goal threshold is **bg*** = (100,860). That is, the mission execution is determined to be below acceptable levels of performance if it takes 100 minutes, or if the time-integrated fire power score is greater than 860. Using the regression metamodels, we see that executing the mission time constraint implies that $ef \geq 0.788$, while meeting the fire

power constraint implies that $ef \geq 0.779$. Thus, from this simple analysis, we can conclude that the threshold ef is given as 0.788.

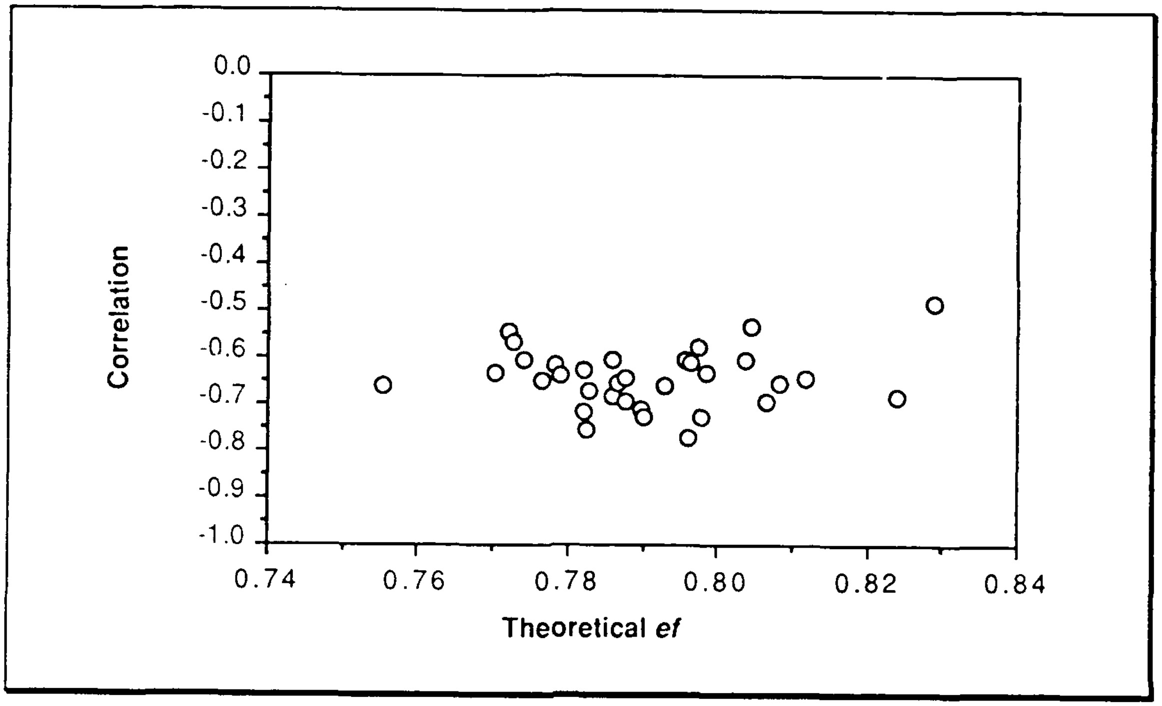

Figure 5.3. Estimated Correlation Coefficients between Time-integrated Fire Power and ($ef - ef$)

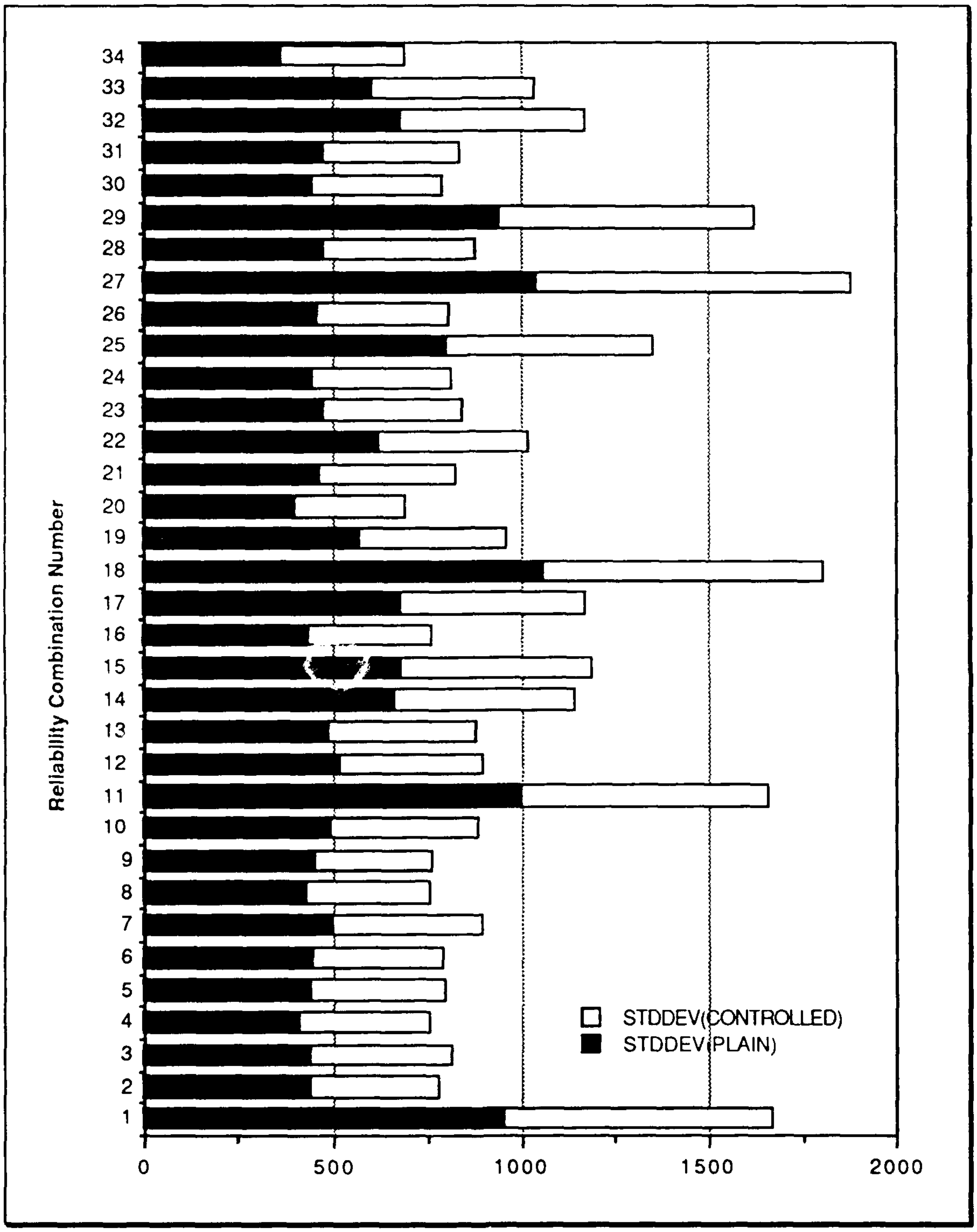

Figure 5.4. Variance Reduction for each Experimental Setting

6.0 CONCLUSION

What we have endeavored to provide to the managers of the U.S. Navy's major caliber ammunition program are the following:

i) a measure of performance which relates defect rates of ammunition components to battle force performance;

ii) a simulation model to assist government analysts in establishing threshold values for the performance measure;

iii) a methodology for prescribing maximum defect rates for ammunition components to ensure that new and stockpiled ammunition conforms to specified threshold levels.

Hence, we have an important set of tools useful in managing procurement and surveillance of ammunition.

It is our view that these tools should be integrated into a system of evaluation, physical experiment, data production, and procurement and surveillance decisions. The weakness of the tools we have produced thus far are that the simulation model is not verifiable—we cannot match simulation output with that of a physical experiment. Figure 6.1 shows our concept of an integrated reliability performance evaluation system. What follows are remarks concerning each component of this system.

6.1 LIVE FIRE EXPERIMENTS

Naval forces use their major caliber guns in exercises and qualification tests and equipment acceptance tests throughout the year. The gun component reliability and recovery time data available through current sources are not very complete and do not address the needs of performance analysis of ammunition. The establishment of our analysis tools should

compel the major caliber ammunition program to identify and collect data from these live fire experiments, especially with regard to gun system failure rates and recovery time.

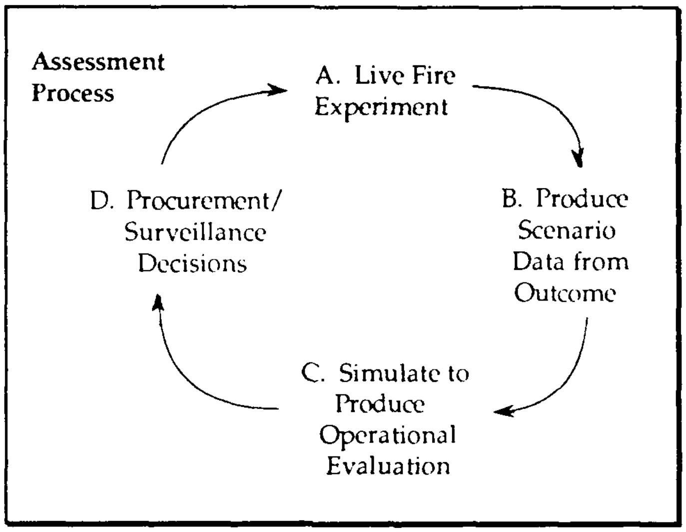

Figure 6.1. Integrated Reliability Performance Evaluation System

6.2 PRODUCE SCENARIO DATA FROM OUTCOME

Using the data from the live fire experiments, scenarios data files should be produced. See Section 3.1.

6.3 SIMULATE TO PRODUCE OPERATIONAL EVALUATION

The produced data files should be subjected to the same analysis process we have executed in Section 4 for the NSWC-supplied scenario. From this analysis, reliability thresholds are established for use in the management of procurement and surveillance processes.

6.4 PROCUREMENT/SURVEILLANCE DECISIONS

Using the threshold values established, the management decisions required are made. This will result in ammunition getting to fleet user which has been affected by this process. The ammunition will thus be used in subsequent live fire experiments. Hence, there will exist a feedback from these decisions to the evaluation of ammunition. The process will become self-tuning.

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